Article no. 21

THE CIVIL ENGINEERING JOURNAL 4-2016

COMPARISON OF PROPAGATION CHARACTERISTICS OF EXCITED STRESS WAVES IN PILE AND ANCHORAGE WITH BOLT SYSTEMS

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ABSTRACT

Dynamic testing methods for pile systems and anchorage-with-bolt systems are similar and often confused with each other, possibly resulting in incorrect assessment of the quality of the pile and the anchorage systems. The stress wave velocity is one of the most important parameters for evaluating the quality of dynamic tests. In this paper, the stress wave velocities in standard concrete specimens of the free rock bolt and the different ages were a reference for comparing the stress wave velocities in a pile-and-anchor system. The tests were conducted using the low strain reflected wave method. Results indicate that the wave velocity in a pile is larger than that in the standard samples, and that the wave velocity in an anchorage-with-bolt system is smaller than that in a free steel bar, but larger than that in a pile and in standard samples. Wave velocities in the pile and in the standard samples were found to raise as the ages of samples increased. The wave velocity in the anchorage-with-bolt system initially decreased as specimen age increased, but increased with increasing specimen age afterward.

KEYWORDS

Low strain reflected wave method, stress wave velocity, pile, anchorage with bolt systém

INTRODUCTION

A pile is the first or sometimes only choice of foundation support for many buildings, while an anchor is generally used to stabilize rock structures. Since both supports are hidden underground structures, it is very challenging to test accurately the quality of the pile and anchorage systems [1, 2]. The reflection wave method is very economical, rapid, simple and highly accurate, so it is most widely used in foundation pile integrity detection and it is the most representative of a dynamic measuring method [3]. Drawing on the principle of pile dynamic testing, use of the reflection wave method to detect the quality of anchor bolts is an effective way to solve the problem of real-time and rapid nondestructive testing of the anchorage quality of anchor bolts [4, 5]. However, care must be taken to address the dynamic testing results for an anchorage system because confusion and misjudgment can be induced if an inappropriate dynamic testing method is used. There is a significant and obvious difference between a pile and an anchorage system, such as the types of loading and defects, physical properties, and so on.

Many investigations have been performed to study the dynamic testing mechanism of both pile and anchorage systems. For instance, boltometer-instrument for nondestructive testing of grouted rock bolts was conducted [6], the stress reflected wave method was used to non-destructively test the bonding integrity of grouted bolts system [7, 8, 9], and high frequency stress wave was used to test grouted density of bolts [10]. Recently, guided ultrasonic wave was applied as a new type of non-destructive detection technique to detect the rock bolts [11, 12, 13]. Numerical simulation of low strain dynamic tests on attenuation and group velocity of guided ultrasonic wave was used to study the non-destructive testing of grouted rock bolts [14, 15, 16]. Researchers have put great efforts on studying stress wave non-destructive testing of anchorage quality for an anchorage system. However, the technology can not be effectively and accurately used to evaluate anchorage quality for bolt systems because the propagation of elastic stress wave in anchorage system is affected by many factors. The consolidation wave velocity is a key parameter for reflecting this propagation and evaluating the anchorage quality[17]. However, consolidation wave velocity has not been studied enough. Consolidation wave velocity was used to test the anchorage quality for an anchorage system [18]. For piles, the PIT (Pile Integritiy Test) low strain instrument was used to test pile integrity [19], and the characteristics of stress wave propagation in pile were studied [20, 21].

These studies show that the stress wave velocity is the key reference parameter for evaluation of construction quality using the reflected wave method. However, these studies are intended either for an anchorage system or for a pile system. As there are similarities between a pile and an anchorage system, a comparative study between them needs to be conducted. In this paper, comparisons between the pile and anchorage systems will be described in terms of the stress wave velocity in the standard concrete specimens of the free rock bolt and the different ages in the standard concrete specimens of piles of different ages and of free rock bolts of different ages.

THE THEORETICAL CALCULATIONS OF STRESS WAVE VELOCITIES IN BOTH SYSTEMS

Stress wave velocity in pile

It is assumed that the medium is a continuous, homogeneous and isotropic elastic material. In a rectangular coordinates $\{x, y, z\}$, if the material damping is neglected, then the propagation of stress wave in an infinite elastic body satisfies a 3-D wave equation,

$$\rho \frac{\partial^2 \varepsilon}{\partial t^2} - {c_3}^2 \left(\frac{\partial^2 \varepsilon}{\partial x^2} + \frac{\partial^2 \varepsilon}{\partial y^2} + \frac{\partial^2 \varepsilon}{\partial z^2}\right) = 0 \tag{1}$$

where t is the elapsed time, ε is the strain, and c_3 is the stress wave velocity under 3-D condition which is related to the density ρ, elastic modulus E and Poisson's ratio μ of medium, and can be written as

$$c_3 = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{2}$$

Considering the diameter of a pile is far less than its length, the stress wave in the pile can be simplified as 1-D stress wave. When the pile vibrates in the longitudinal direction, the cross section is assumed to be a still plane with an uniform distribution of stress. Based on the d'Alembert's principle and Hook's law, the wave equation for the pile can be further given as,

https://doi.org/10.14311/CEJ.2016.04.0021

$$\frac{\partial^2 u}{\partial t^2} - c_1^{\,2}\frac{\partial^2 u}{\partial x^2} = 0 \tag{3}$$

where c1 is the stress wave velocity under 1-D condition. By neglecting the lateral influence, the wave velocity is only related to ρ and E, and Eq. 2. can be simplified as

$$c_1 = \sqrt{\frac{E}{\rho}} \tag{4}$$

For low strain condition, the 1-D wave equation given above is adopted. In the pile system, the wave velocity in pile is actually equal to that in medium as ρ and E representing density and elastic modulus of medium. Whenever the depth of shallow defects is required, a 3-D description of the wave velocity in the pile must be made using Eq.2 [22]. This can be illustrated by a simple calculation example. If $\mu = 0.2$, then we have $c_3 = 1.05c_1$, suggesting that the wave velocity in pile is bigger than that in medium, and 1-D simplification may deteriorate the testing accuracy. In addition, Eq.2.and Eq.4.only take into account the influence of medium but neglect that of steel bars, thereby obtaining a smaller value of wave velocity than the real one in pile.

Stress wave velocity in anchorage system

The dynamic testing of pile is concerned with the problem of pile defects, while it is a little relation with the surrounding media. So the wave velocity mainly refers to that in the pile medium. For the anchorage system, the dynamic testing is purposely used to determine the bonding effect between the bolt and surrounding medium, and consequently wave velocity on the interface between the bolt and the surrounding medium is of interest. If the bolt can be seen as a 1-D rod member, the wave velocity in anchorage system can be obtained as

$$c' = \sqrt{\frac{E'}{\rho'}} \tag{5}$$

where c' is the wave velocity in anchor system, and E' and ρ' are equivalent elastic modulus and density of the anchorage system.

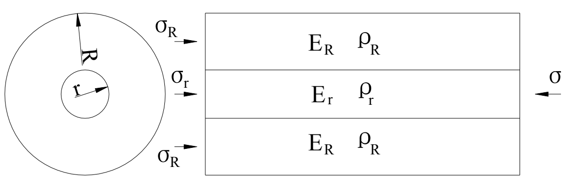

Figure 1 - Calculation model for anchorage systém

Figure 1 depicts a unit from the anchorage segment. Note that, r, E_r, and ρ_r, are the radius, the elastic modulus and density of bolt, respectively; while R, E_R, and ρ_r, stand for those of the anchorage system, correspondingly. It is assumed that both the bolt and anchorage medium are isotropic elastic, and that their longitudinal deformations are compatible. σ and ε are the stress acting on the unit body and corresponding strain, with the subscripts r and R denoting pile and anchorage systems, respectively. Based on the principle of mass conservation (Eq.6.), the equilibrium condition of force (Eq.7.), the constitutive relation of materials (Eq.9.) and the condition of deformation compatibility (Eq.8.), as listed below:

$$\rho\pi R^2 = \rho_r \pi r^2 + \rho_R \pi (R^2 - r^2) \tag{6}$$

$$\sigma\pi R^2 = \sigma_r \pi r^2 + \sigma_R \pi (R^2 - r^2) \tag{7}$$

$$\varepsilon = \varepsilon_R = \varepsilon_r \tag{8}$$

$$\varepsilon = \frac{\sigma}{E}, \varepsilon_R = \frac{\sigma_R}{E_R}, \varepsilon_r == \frac{\sigma_r}{E_r} \tag{9}$$

the equivalent elastic modulus (E') and density (ρ') are obtained

$$E' = E_R \frac{R^2 - r^2}{R^2} + E_r \frac{r^2}{R^2} \tag{10}$$

$$\rho' = \rho_R \frac{R^2 - r^2}{R^2} + \rho_r \frac{r^2}{R^2} \tag{11}$$

substituting E' and ρ' back to Eq.5. leads to the wave velocity as

$$c' = \sqrt{\frac{E_R(R^2 - r^2) + E_r r^2}{\rho_R(R^2 - r^2) + \rho_r r^2}} \tag{12}$$

in extreme conditions, like for $r \to 0$, c' is equal to the wave velocity in anchor medium, and for $r \to R$, c' is then equal to the wave velocity in free steel bar.

DETERMINATION OF WAVE VELOCITIES

Test system

Based on the reflected wave method, the wave velocities in two (pile and anchorage) systems were obtained by a testing system including an AVANT-10 dynamic signal analysis system, an amplifier, two transducers and a computer. The wave velocities in the standard concrete test block were measured by using ZBL-U520 non-metal ultrasonic testing device.

Measurement of wave velocities

In order to avoid effects of other factors on the wave velocities, tests for both pile and anchorage systems were carried out on the same laboratory model as shown in *Figure 2*. For pile, the force-hammer vertically acted on the medium close to the steel bar. For anchorage system, the force-hammer vertically acted on the steel bar. The reflection time was determined by the analysis of the time domain. If the travel time of reflection wave at the bottom of the pile is T1, that at the bottom of the bolt is T2, then these two respective wave velocities can be obtained,

$$c^P = \frac{2L}{T_1} \tag{13}$$

$$c^A = \frac{2L_2}{T_2 - 2L_1/V_b} \quad (14)$$

where c P and cA are the tested stress wave velocities in the pile and anchorage systems, respectively. L, L1, and L2 are the length of the pile, the free and grouted lengths of the bolt, respectively. $V_b = 5100m/s$ is the wave velocity in the free bolt.

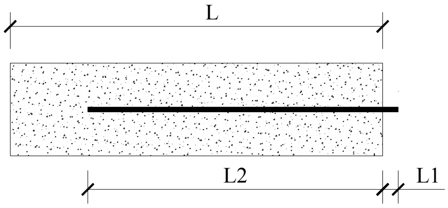

Figure 2 - Structure of member

Laboratory test models

There were two test models constructed in a laboratory to study the stress wave velocity in both pile and anchorage systems, and their details are listed below. Model 1 (*Figure 3*) was cast into one standard concrete block with a dimension of 600mm×600mm×2400mm, with the steel bars of 2.0 m in length and 28 mm in diameter embedded in the centre. The mixing proportion of water, cement, sand and gravel in the cubic concrete block was 1: 2: 4: 8. The grouted length of the steel bar in concrete was 1.9m, and the free length was 0.1m. The size of the standard cubic concrete specimens was 150mm×150mm×150mm. Model 2 was built with mortar in a PVC pipe of 2.0m in length and 200mm in diameter, also with the same steel bar in the centre. The mix proportion of water, cement and sand in Model 2 is 1: 2: 4. The grouted and free lengths of the steel bars are the same as in the Model 1. The size of the standard cubic mortar specimens was 70.7mm×70.7mm×70.7mm.


Figure 3 - Model in laboratory

RESULTS AND DISCUSSIONS

Table 1 - Cube compressive strength of concrete and wave velocities related to Model 1 at various curing time

Curing time / d	Strength / Mpa	Anchorage system $/m/s$	Pile $/m/s$	Concrete $/m/s$
1	3.2	4864	2892	2891
3	11.7	4691	3070	2979
5	16.1	4578	3288	3072
7	17.9	4506	3357	3269
9	19.4	4343	3529	3339
11	23.1	4145	3582	3491
14	25.7	4099	3636	3518
21	27.3	4180	3692	3572
28	30.5	4193	3746	3686

Table 2 - Cube compressive strength of mortar and wave velocities related to Model 2 at various curing time

Curing time / d	Strength / Mpa	Anchorage system / m / s	Pile / m / s	Mortar / m / s
1	5.3			2215
3	7.9	4442	3113	2499
5	10.1		3171	2630
7	13.4	4422	3288	2778
9	15.6			3003
11	18.3			3066
14	19.2	4235	3390	3132
21	24.8	4285	3438	3269
28	26.3	4389	3518	3420

Tables 1 and *2* list the information about cube compressive strength of concrete and stress wave velocity related to the Model 1 and the Model 2, respectively, at different curing time intervals. The relationships between the cube compressive strength of the mediums, the curing time, and the stress wave velocity for both Model 1 and Model 2 are depicted in *Figures 4* through *8* and *Table 3*. Discussions are provided below.

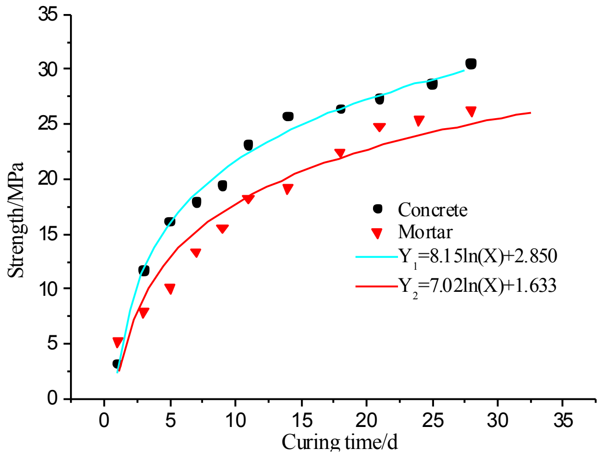

Figure 4 - Relationship between the cube compressive strength of medium and curing time

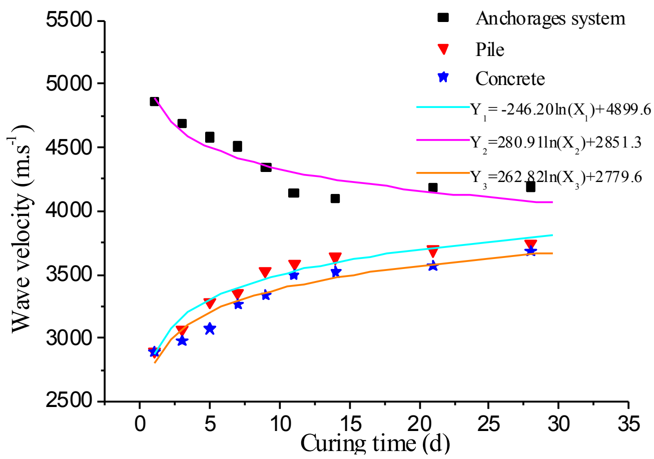

Figure 5 - Relationships between wave velocities of model 1 and curing time

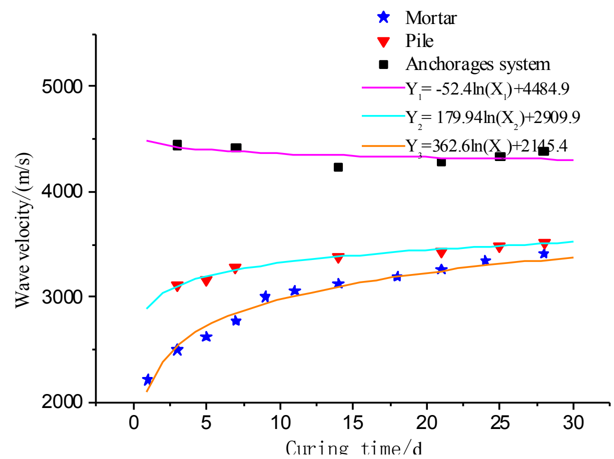

Figure 6 - Relationships between wave velocities of model 2 and curing time

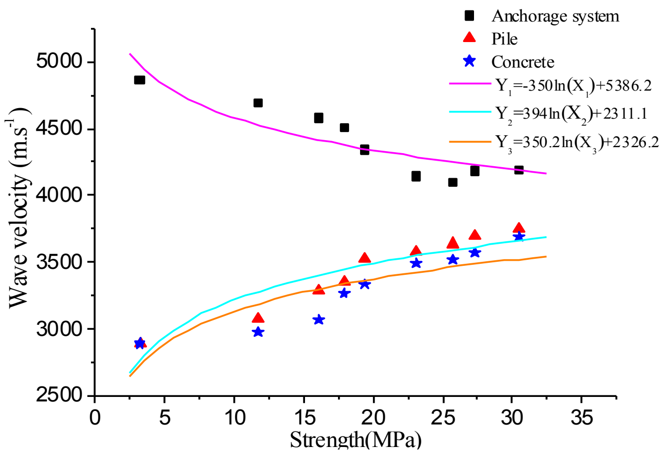

Figure 7 - Relationships between wave velocities of model 1 and cube compressive strength

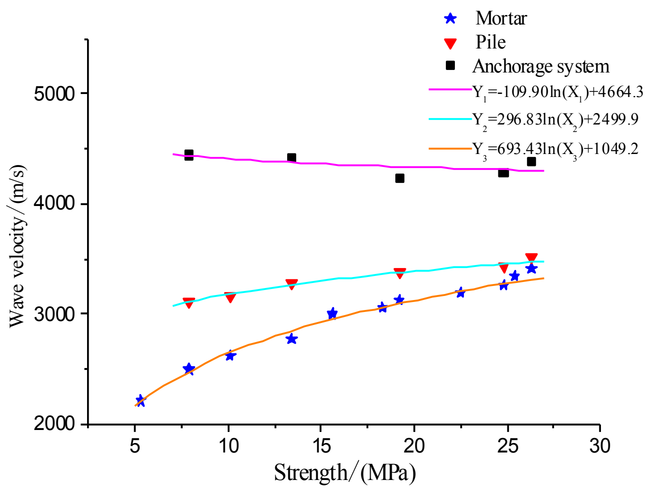

Figure 8 - Relationships between wave velocities of model 2 and cube compressive strength

Table 3 - Correlation coefficient of the fitting curve from Figures 4 to Figures 8

Figure	Fitting curve	Average	Variance	Coefficient
4	Y1	22.05	62.90	0.924
	Y2	18.44	48.22	0.922
5	Y1	3547.39	57523.06	0.921
	Y2	4289.52	44185.90	0.921
	Y3	3430.86	50352.89	0.921
6	Y1	4355.48	2160.05	0.914
	Y2	3354.33	25471.64	0.914
	Y3	3040.99	103432.50	0.914
7	Y1	4456.40	66814.47	0.942
	Y2	3352.63	83968.41	0.943
	Y3	3272.74	59375.54	0.949
8	Y1	4360.62	1883.41	0.985
	Y2	3320.10	13739.30	0.985
	Y3	2901.50	112519.40	0.977

(1) Characteristics of wave velocity in the anchorage system

In the early stage of curing process, the medium has a very low mechanical strength, and thus the reflection signal at the fixed end of the bolt is not obvious. The mortar medium does not closely envelop the bolt, resulting in low bond strength at the interface between the medium and the bolt. The wave velocity in an anchorage system is close to that in the free bolt during the early curing stage.

With the elapse of curing time, the strengths of both the medium and the bond at the concrete and bolt interface increase, the reflection signal at the fixed end gradually becomes stronger, and the travel time of reflection wave at the bottom of the bolt increases. It can be found that the wave velocity in anchorage system decreases with the curing time.

However, about 14 days later, the travel time of the reflection wave to the bottom of the bolt begins to decrease. The medium strength and bond strength are observed to slowly increase, indicating the gradual improvement in the anchorage quality. The wave velocity in the anchorage system steadily increases but lies between those measured in the free bolt and in the medium.

(2) Variation characteristics of wave velocity in pile

It can be seen that the wave velocity in the pile is the same as that in the medium of the pile, but different from that at the medium-bolt interface in the anchorage system and also different from that in standard specimen. As observed in figures, the evolution of wave velocity in the pile is similar to that in medium. The increases in the medium strength, and wave velocities in both pile and medium correspond to the curing time, but their variation magnitudes are greater during the first 14 days than subsequent 14 days.

(3) Comparison of wave velocities in the pile and anchorage systems

There are some similarities between the wave velocities in a pile system and in an anchorage system. The correlation coefficients between the wave velocities in both systems and curing time of samples are 0.914. Likewise, the correlation coefficients between wave velocities and cube compressive strength exceed 0.942, and the correlation coefficients between the cube compressive strengths of specimens and curing time exceed 0.922. Correlation coefficients that exceeded 0.8 were exhibited between the two variables. Thus, the wave velocities in a pile system and in an anchorage system are very strongly correlated with curing time and cube compressive strength, whereas the cube compressive strengths of the surrounding medium in a pile system and an anchorage system have high correlations with curing time.

The previous analysis shows that the wave velocity in the pile system is mainly determined by the changing property of the medium, but also affected by the steel bar due to a 3-D effect mentioned before. However, the characteristics of wave velocity in the anchorage systems are quite different, which is controlled by the conditions of both the medium and the bond at the medium-bolt interface, or more concisely by the anchorage quality. The bigger the bond strength, the better the anchorage quality, and the closer the wave velocity in anchorage system to those in pile and medium. Contrarily, the smaller the bond strength, the worse the anchorage quality, and thus the closer the wave velocity in anchorage system to that in free steel bar.

CONCLUSIONS AND DISCUSSIONS

In this paper, comparisons have been made on wave velocity in pile and anchorage systems. Different functional mechanisms have been identified and new equations for wave velocity have been proposed for pile and anchorage systems, respectively. The proposed method has been properly validated with laboratory experiments. Summary of the investigation on the propagation of wave velocity in pile and anchorage systems are given below:

(1) Wave velocity in a pile system is completely different from that in an anchorage system. In pile systems, wave velocity is closely related to the cube compressive strength and shows a rising trend as a function of curing time, and increasing amplitudes gradually stabilize as curing time increases . In anchorage systems, wave velocity is mainly dependent on the bond strength of the interface between the support medium and steel, decreasing in the early stage and then increasing afterwards. Wave velocity in anchorage systems is larger than that in both pile systems and the surrounding medium.

(2) Using the least square method to deal with the data, the regression equation and the fitting curve are got. The fitting curves are in line with the logarithmic function relationship. All the correlation coefficients of fitting curves reach more than 0.914.

(3) Using the least squares method to analyze data resulted in regression equations and fitting curves that described the test results. The fitting curves take the form of logarithmic functions. In practical work, the drawing datas of standard working curve are often used in a linear equation, and a linear equation can be reduced to a curve equation, which can be used to realize the curve fitting of the data.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Scientific Research Fund of the National Natural Science Foundation of China (NO.51204098), the Natural Science Foundation of Hunan Province of China (NO.11JJ6045), and the Research and Development Plan of Hunan Province of China (NO. 2015SK2058-4).

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